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EVALUATION OF TWO BALLISTICALLY TOLERANT FORWARD BELL CRANK CONCEPTS FOR THE CH-47 HELICOPTER

By

I. E. Figge, Sr.

November 1971

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA 23604

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House Task PS 70-7
USAAMRDL Technical Report 71-63
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ABSTRACT

The overall objective of this research program was to investigate a ballistically tolerant, lightweight, low-cost flight control system for the forward rotor control of the CH-47 helicopter. Both "Tetra-Core" (a three-dimensional, filament-wound space structure) and tubular fiberglass cloth concepts were evaluated. Weights of less than 2 pounds were achieved, as compared to 3. 4 pounds for the existing metallic bell crank. Of the two basic concepts, "Tetra-Core" offers structural superiority, whereas the glass cloth offers ease of fabrication and cost effectiveness superior to the existing metallic components. It was found that venting reduced the damage on the exit side of the glass cloth specimens. In addition to the bell crank, ballistically tolerant push rods and bearings were investigated. Limited research on the components indicates favorable tolerance to ballistic impact, along with potential weight and cost savings.

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FOREWORD

This report was prepared under Department of the Army Task 1F162208A17003, House Task PS 70-7.

The author acknowledges Messrs. M. C. Dail, B. L. Karp, E. H. McIlwean, and C. L. Oaten, all of the Structures Division, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, for their significant contributions to both design and fabrication of the flight control components. Without their aid, this program would not have been possible.

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INTRODUCTION

A significant percentage of the helicopter losses in Southeast Asia have resulted from damage caused by small-arms fire (7.62mm) on flight control components.[1] In general, the existing components are designed with minimum dimensions to save space and weight and are fabricated from notch-sensitive metallics. Unfortunately, this approach renders these components exceptionally vulnerable to catastrophic failure on ballistic impact. In order to improve ballistic behavior, both new design concepts and new materials are required.

The basic design philosophy for achieving ballistic tolerance is:

1. Design component to localize damage upon ballistic impact.
2. Use redundant load path designs.
3. Use notch-insensitive materials.

Previous research substantiated that this philosophy produced significant improvements in the ballistic tolerance of several categories of flight controls, including CH-47 pitch links, bell cranks, and idler arms[2] and UH-1 pitch links and control quadrants.[3] One of the components in Reference 2, namely, the forward bell crank for the CH-47 helicopter, although achieving the desired ballistic behavior, was of particular interest because the fabrication technique selected resulted in a part weighing considerably more than the existing metallic component (5.5 pounds as compared to 3.4 pounds). The design incorporated a tape-wound fiberglass "billiard rack", a foam core, and shaped fiberglass cloth face sheets (see Figure 1). In addition to weighing more, the estimated production cost was almost an order of magnitude greater than that of the existing component.

In general, composite structures can be designed to be lighter than their metallic counterparts. Based on this premise, a research program was undertaken with the overall objective of achieving ballistically tolerant, lightweight, low-cost flight control components for helicopters. The bell crank from the forward rotor control system of the CH-47 was selected as a representative component for this purpose (see Figure 2).

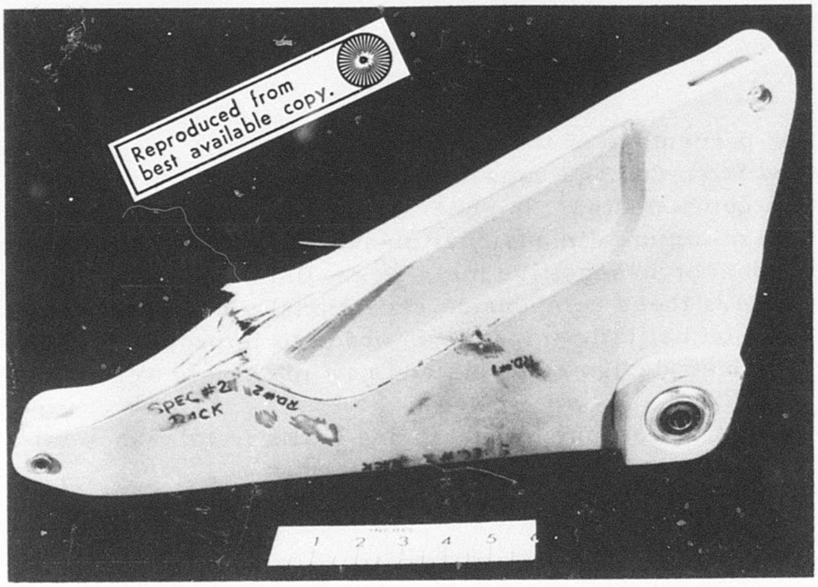

Figure 1. Boeing-Vertol Ballistically Tolerant CH-47 Forward Bell Crank After Ballistic Impact.

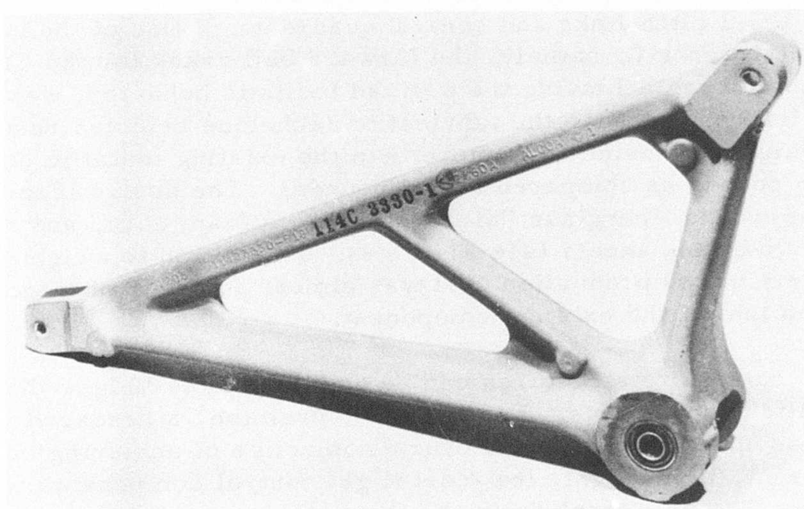

Figure 2. Existing Metallic CH-47 Forward Bell Crank.

BELL CRANK DESIGN

Design goals for the bell crank were established in this program:

1. Lighter weight than existing component (3.4 pounds)
2. Production cost less than for existing component ($134.80)
3. Operating temperature range from -65°F to 180°F
4. Corrosion resistance
5. Interchangeability with existing component
6. Capability of withstanding at least 2000 fatigue cycles at maximum flight load conditions after sustaining two fully tumbled .30-caliber impacts

Two general design concepts were evaluated, one using "Tetra-Core" and the other using fiberglass cloth. This report covers the fabrication techniques; the results of static, dynamic, and ballistic tests; and an overall evaluation of the components.

"TETRA-CORE" BELL CRANK

"Tetra-Core" (see Figure 3 and Reference 4), which is a three-dimensional, filament-wound space structure developed at the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, has demonstrated exceptional ballistic tolerance. Due to its desirable ballistic behavior, its high strength-to-weight ratio, and its inherent redundant design, it was selected as a candidate structure.

Fabrication of the bell crank is as follows (see design drawing, Figure 4):

1. Cut "Tetra-Core" pattern in balsa wood form, tetrahedron size 0.75 inch base by 0.50 inch height, wall thickness 0.050 inch (Figure 5).
2. Lay 20-end S-glass roving in slots (Figure 6); resin impregnate with Epon 828 epoxy resin/Z curing agent; cure at 175°F for

2 hours; post cure at $300^{\circ}F$ for 2 hours.

3. Cut bell crank faces to shape (Figure 7).

4. Mill bearing attachment area 0.050 inch, both sides.

5. Bond precured five-ply 181 cloth/Epon 828 resin/DTA curing agent to faces in bearing attachment area with 828 resin/DTA, and drill to accommodate bearing (Figure 8).

6. Cut 1.3 lb/ft^3 foam core to shape. Notched areas are to facilitate installation and removal of push rods (Figure 9).

7. Jig align face sheet and core; bond together 828/DTA (Figure 10).

8. Fabricate restraining strap on mandrel with three-ply 181 cloth/one-ply 3M 1002 unidirectional tape/four-ply 181 cloth, 828 resin/Z; vacuum bag; cure; slot to accommodate push rods (Figure 11).

9. Bond restraining strap to face sheets with 828 resin/DTA.

The completed assembly is shown in Figure 12. The design incorporated ballistically tolerant bearings and push rods, which are discussed in a later section. The final weight of the component without push rods was 2.5 pounds, as compared to 3.4 pounds for the existing metallic component. The component can be fabricated without the balsa form, resulting in a weight of 2 pounds.

No attempt was made to optimize the "Tetra-Core" face sheets (test results will indicate that the component was substantially overdesigned).

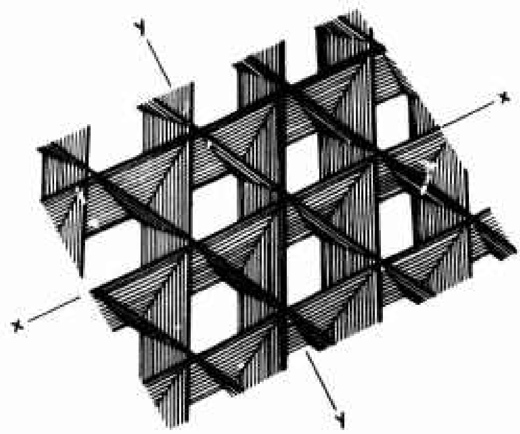

Figure 3. Filament-Wound "Tetra-Core" Element.

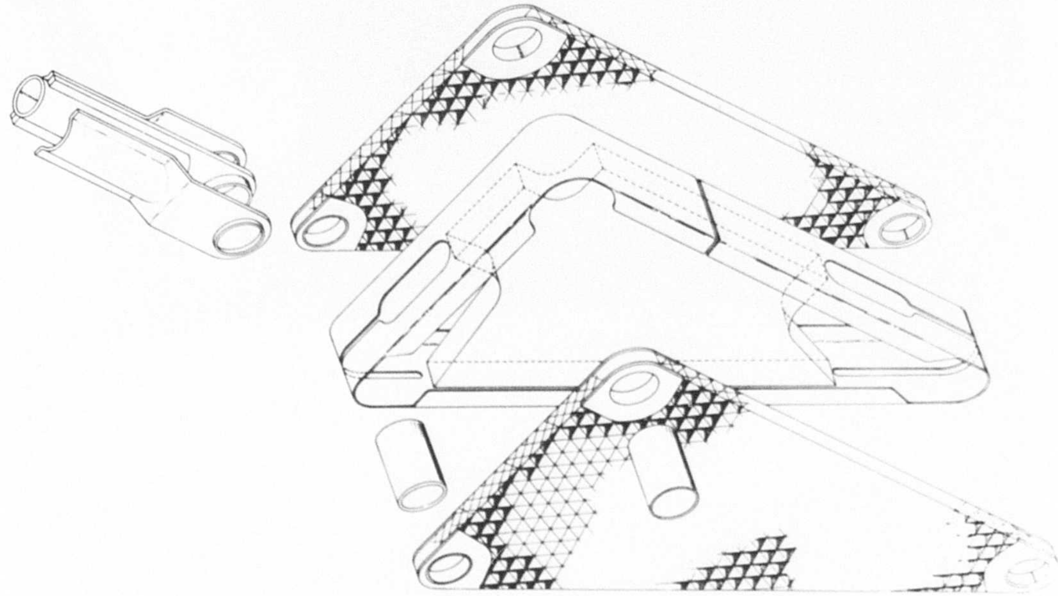

Figure 4. Exploded View of "Tetra-Core" Bell Crank.

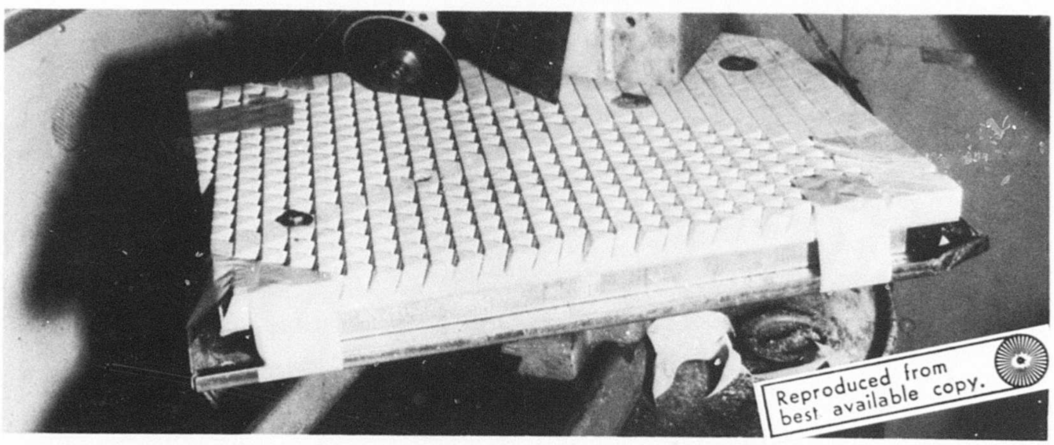

Figure 5. Cutting of Balsa Wood "Tetra-Core" Form.

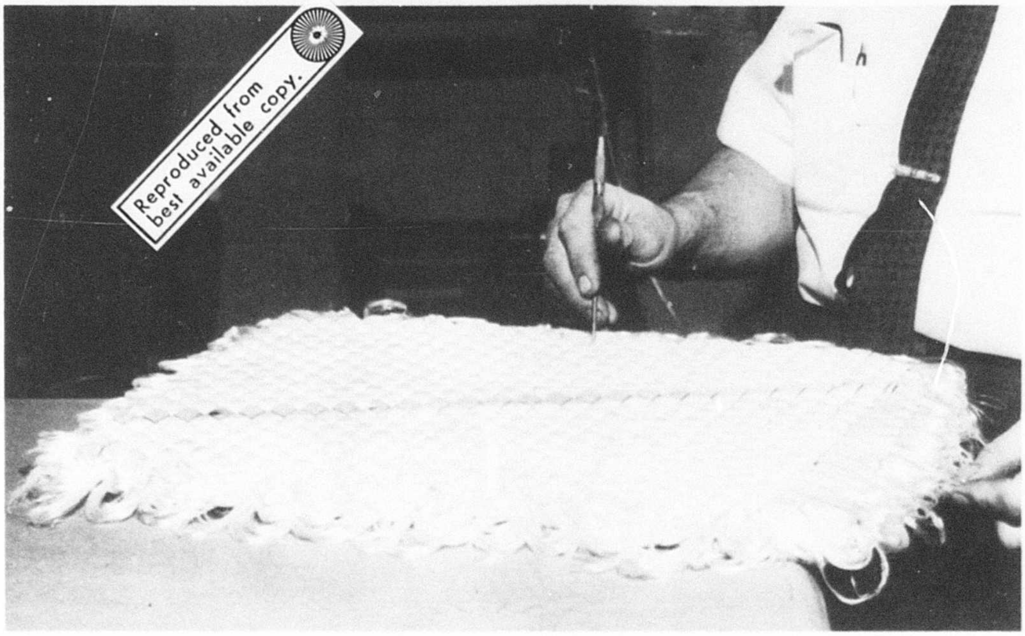

Figure 6. Positioning 20-End S-Glass Roving in Balsa Form.

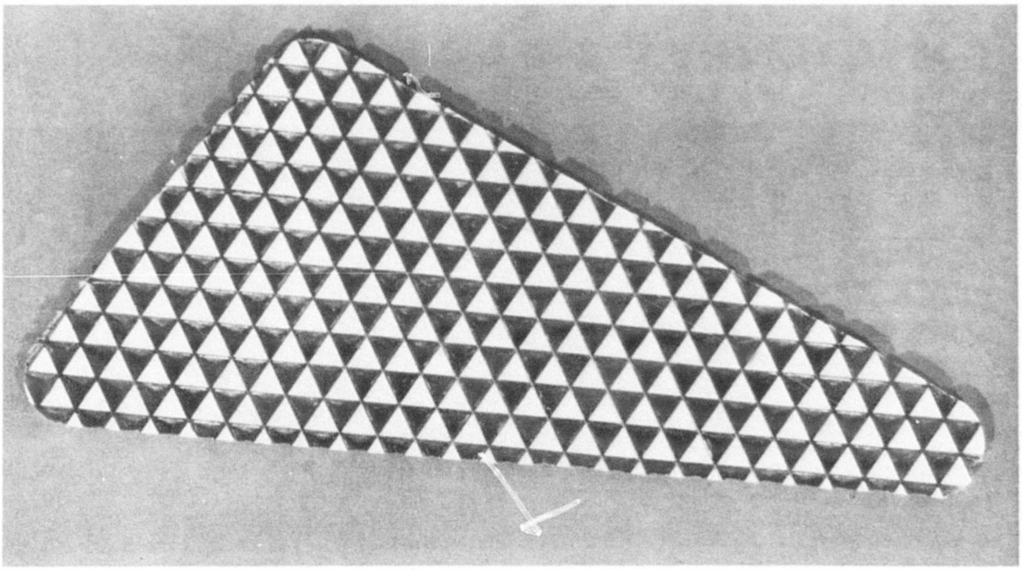

Figure 7. "Tetra-Core" Bell Crank Face Sheet Cut to Shape.

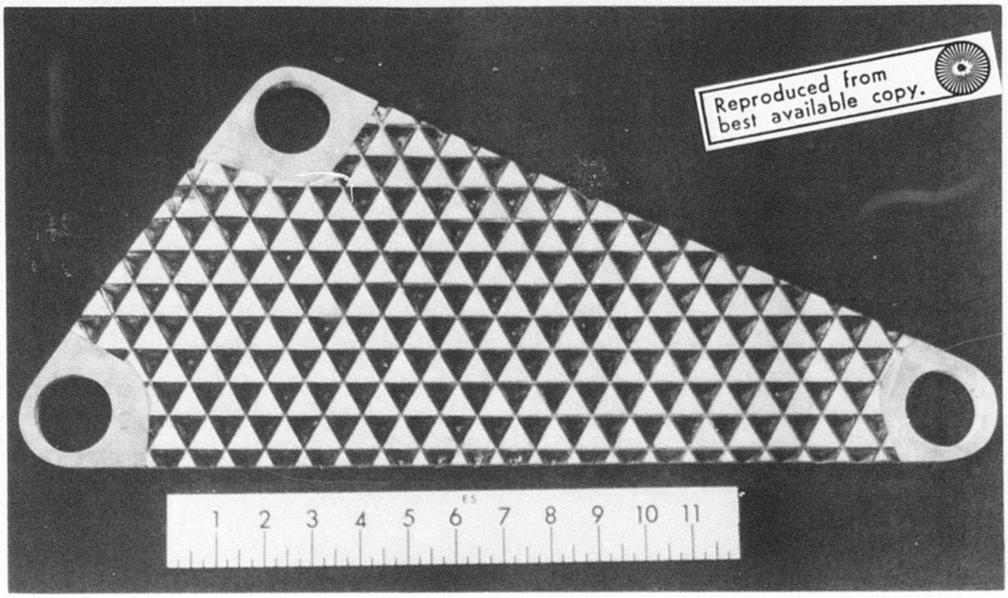

Figure 8. "Tetra-Core" Face Sheet With Precured 181 Glass Cloth Bearing Attachments.

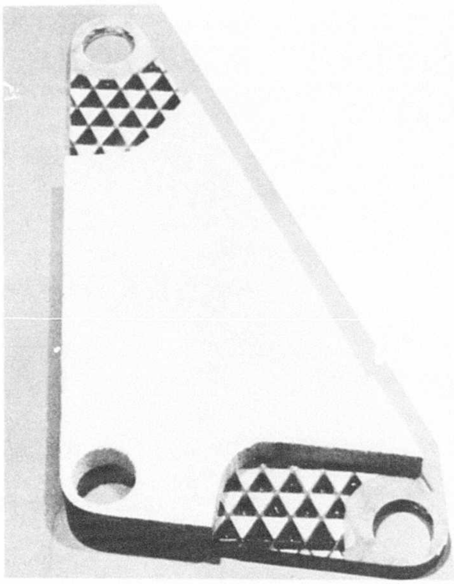

Figure 9. Foam Core Cut to Shape.

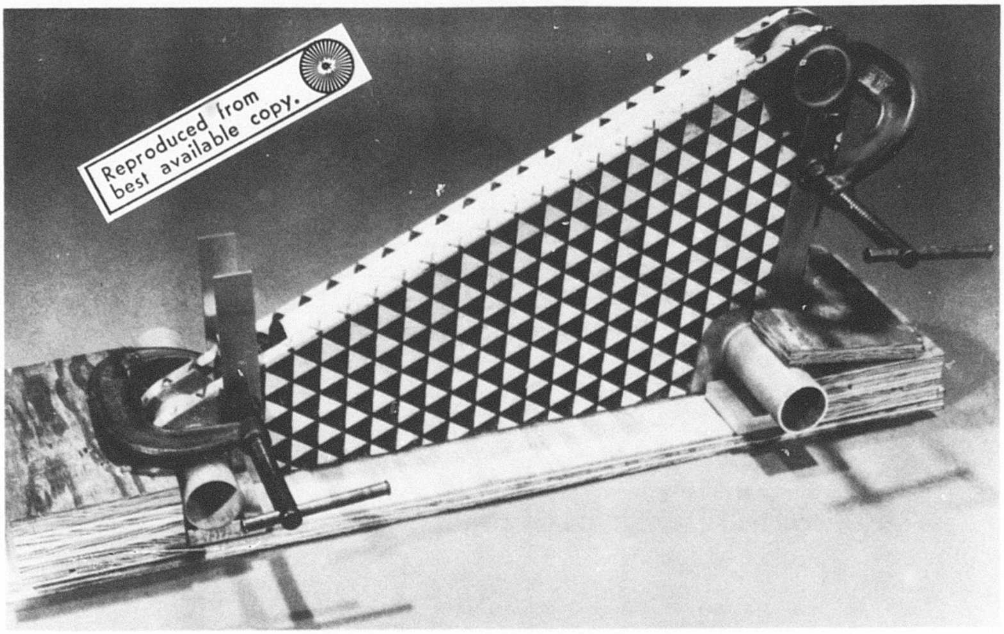

Figure 10. Alignment and Assembly Procedure.

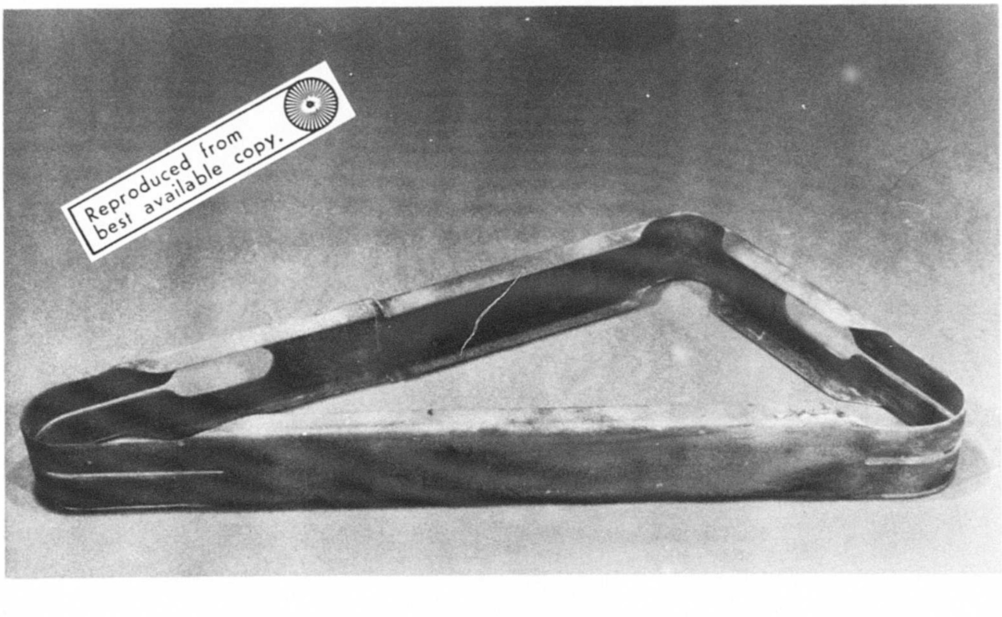

Figure 11. Preformed Restraining Strap.

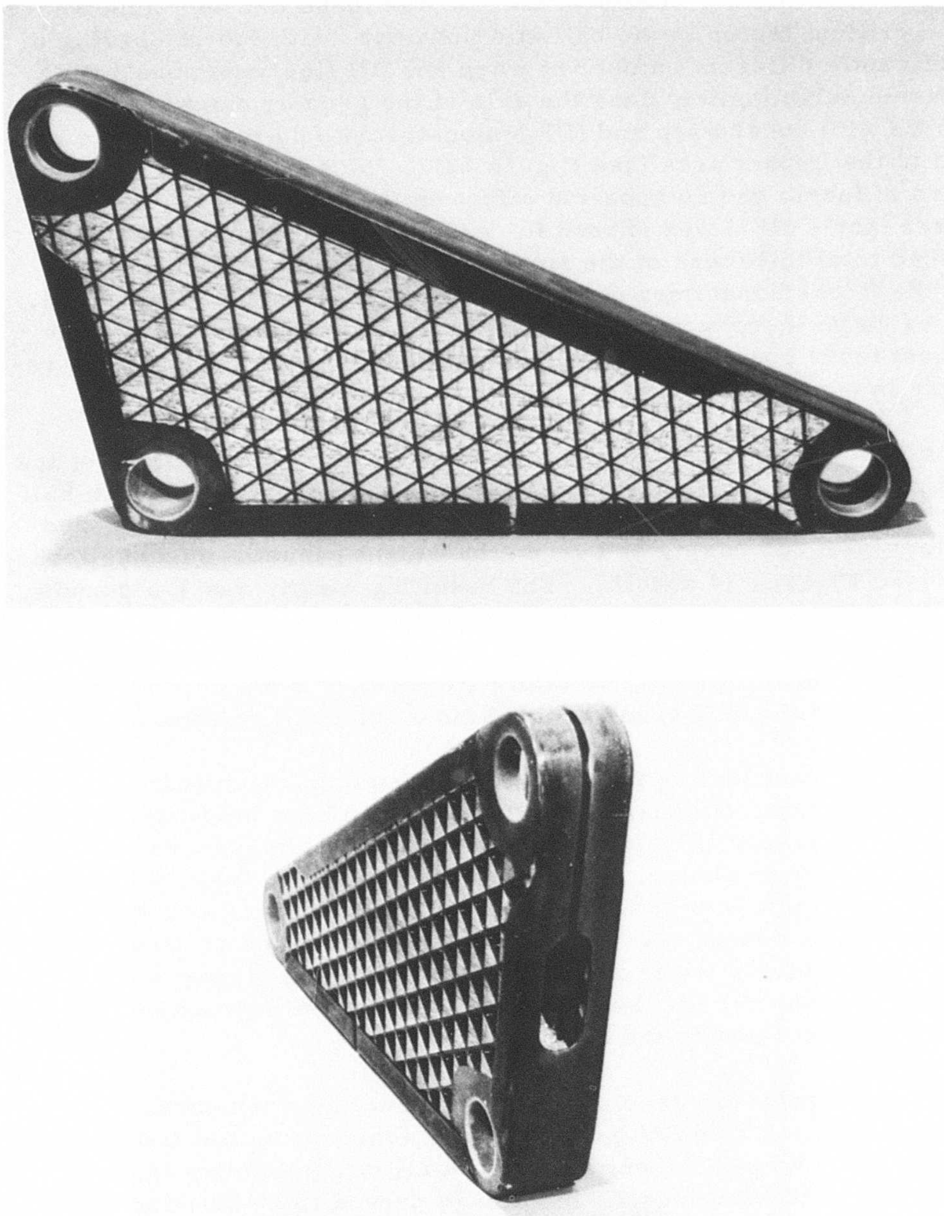

Figure 12. Completed "Tetra-Core" Bell Crank.

FIBERGLASS CLOTH BELL CRANK

The second design approach was to use fiberglass cloth, which was chosen because of its desirable ballistic behavior and because it can produce cost-effective components. It was found that the cloth weave was a critical factor in the ballistic behavior, with fabrics having a significantly different number of warp and fill fibers demonstrating extensive delamination along the axis of the greater number of fibers. Fabrics with equal warp and fill demonstrated only local damage confined to the impact area (see Figure 13). Thickness of the individual layers of fabric had no apparent effect on the behavior; therefore, a thicker fabric (181) was chosen for ease of fabrication. However, finished total thickness of the specimen did influence the behavior, with the thicker specimen demonstrating more damage. Therefore, the design philosophy was to use 181 cloth in a specimen having the thinnest faces possible, thus improving the ballistic behavior and resulting in a weight savings.

Three concepts were evaluated, the latter being improvements of the earlier. The first design was a "clamshell" approach with each half premolded and cured (four-ply 181 cloth/828/DTA) and then bonded together with 828 resin, 30 percent by weight phenolic microballoons/DTA (see Figures 14 and 15). The resulting weight was 1.6 pounds, including fiberglass cloth bearings (described in a later section). Although the "clamshell" bell crank carried approximately the required load before static failure (see table, page 19), the deflections were excessive and the bell crank buckled out of plane at relatively low loads.

To alleviate the buckling problem, the second approach incorporated preformed six-ply 181 glass cloth tubular members held together with preformed four-ply 181 glass cloth face sheets (see Figures 16 and 17). As in the previous design, the weight, including bearings, was 1.6 pounds. Although this design solved the deflection problem encountered in the previous design, failures consistently occurred in attachment areas at load levels lower than desirable. Several attempts were made to reinforce these areas; however, the fabrication difficulties and increase in weight did not justify the effort.

The third concept was developed to overcome the attachment failure problem. It consisted of square tubes, a foam core, and flat face sheets reinforced in the attachment area. The initial specimens again incorporated glass cloth bearings. This design proved to be satisfactory in ease of fabrication and structural and ballistic behavior.

In order to better evaluate the square tube concept and to compare it with the existing metallic component and the "billiard rack" bell crank of Reference 2, a finite-element optimization of the design was undertaken. The results indicated that three-ply 181 glass cloth face sheets and six-ply 181 glass cloth tubes would be structurally sufficient. A foam core was not required.

Due to minimum gage considerations, four-ply face sheets were used. In order to make the component fit and function in the CH-47 helicopter, existing metallic bearings were incorporated. The resulting weight was 1.9 pounds. Following is a brief description of the fabrication procedure (see design drawing, Figure 18):

1. Preform three six-ply WBC3201 epoxy prepreg square tubes, and cut to mate in a triangular planform.

2. Preform four-ply WBC3201 epoxy prepreg face sheets with three-ply doublers, and cut to shape.

3. Preform four-ply WBC3201 epoxy prepreg end attachment channels.

4. Bond face sheets and channels to tubes with FM 1000 adhesive.

5. Jig drill bearing and sleeve holes, and install bearings and sleeves.

A completed bell crank is shown in Figure 19.

It is estimated that in production, the cost per bell crank would be $75.00, which is substantially below the current cost of $134.80 for the metallic component.

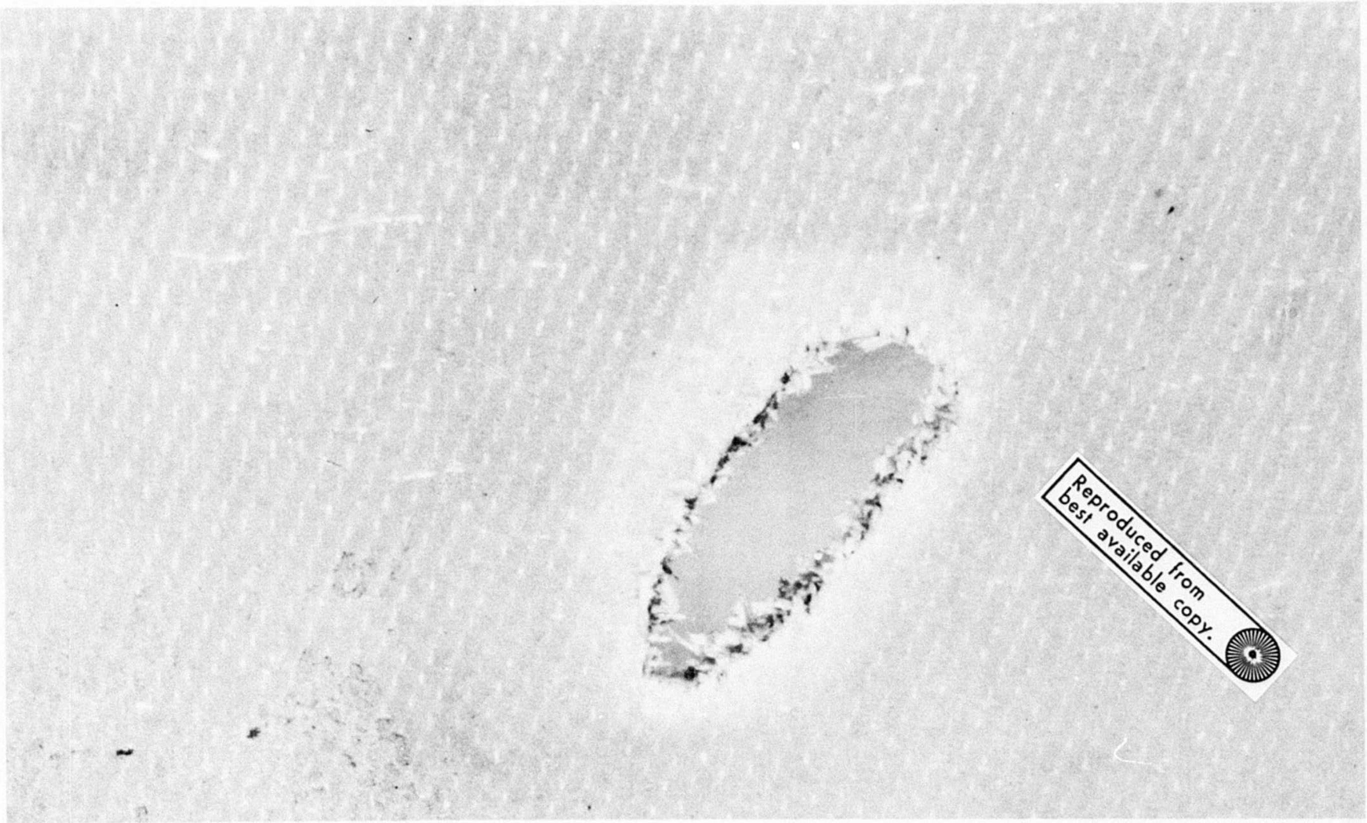

Figure 13. Ballistic Damage on Four-Ply 120 Glass Cloth Specimen.

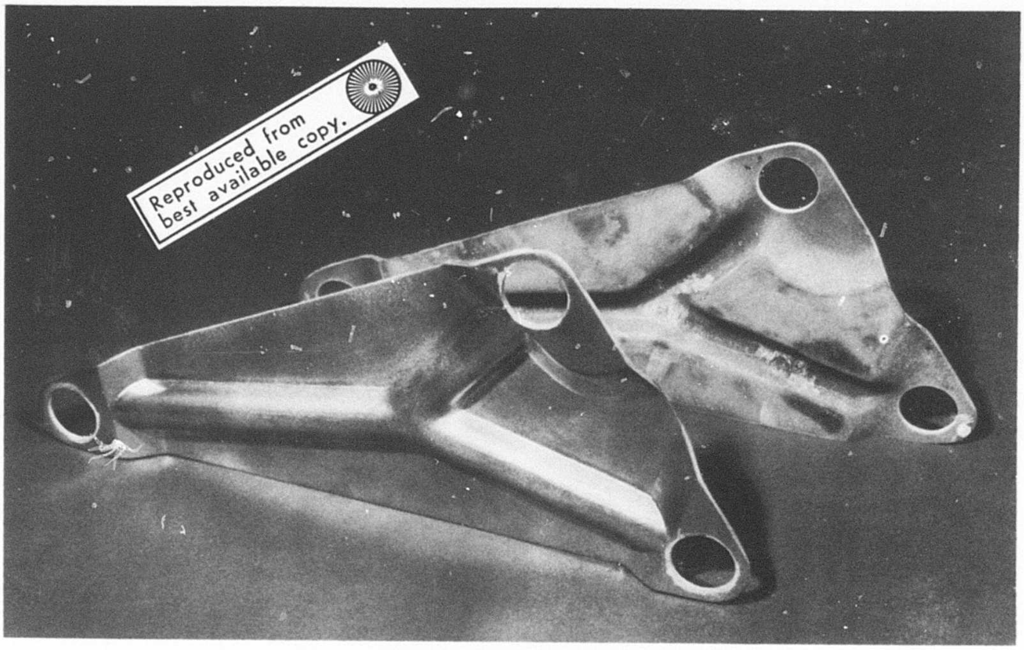

Figure 14. Clamshell Bell Crank Before Assembly.

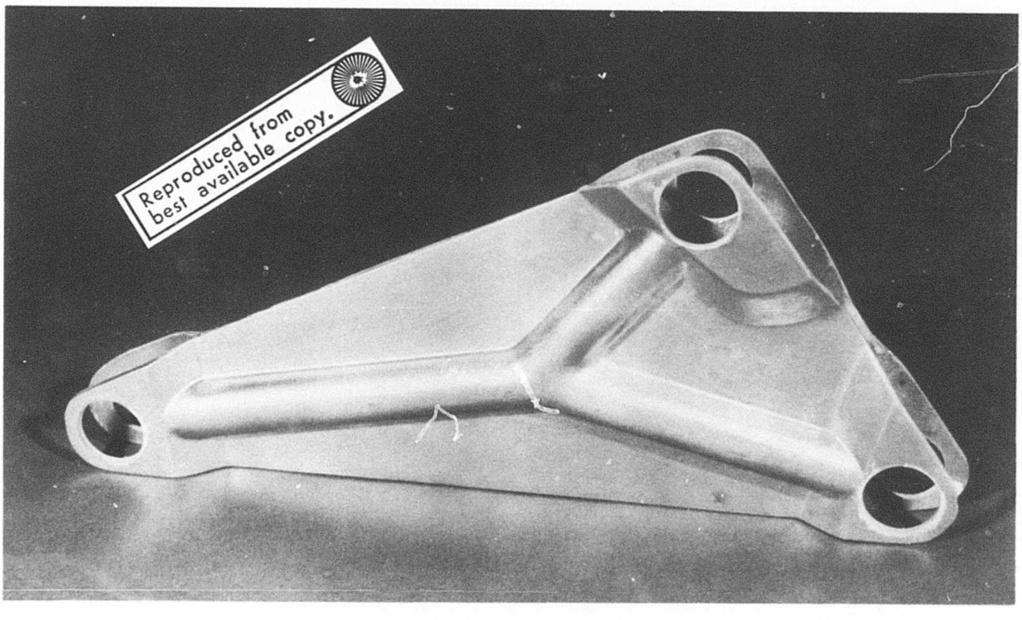

Figure 15. Clamshell Bell Crank After Assembly.

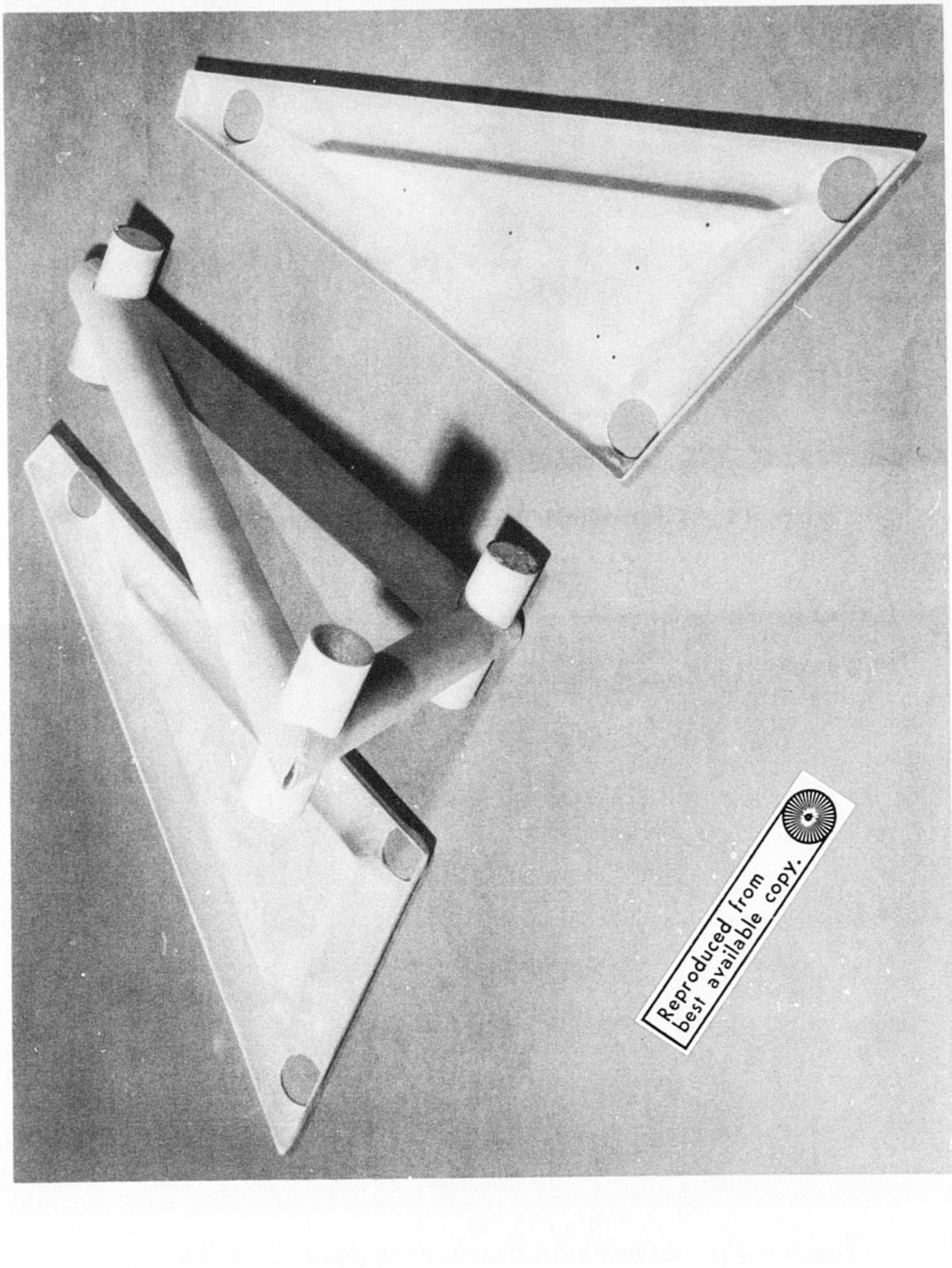

Figure 16. Tubular Bell Crank Before Assembly.

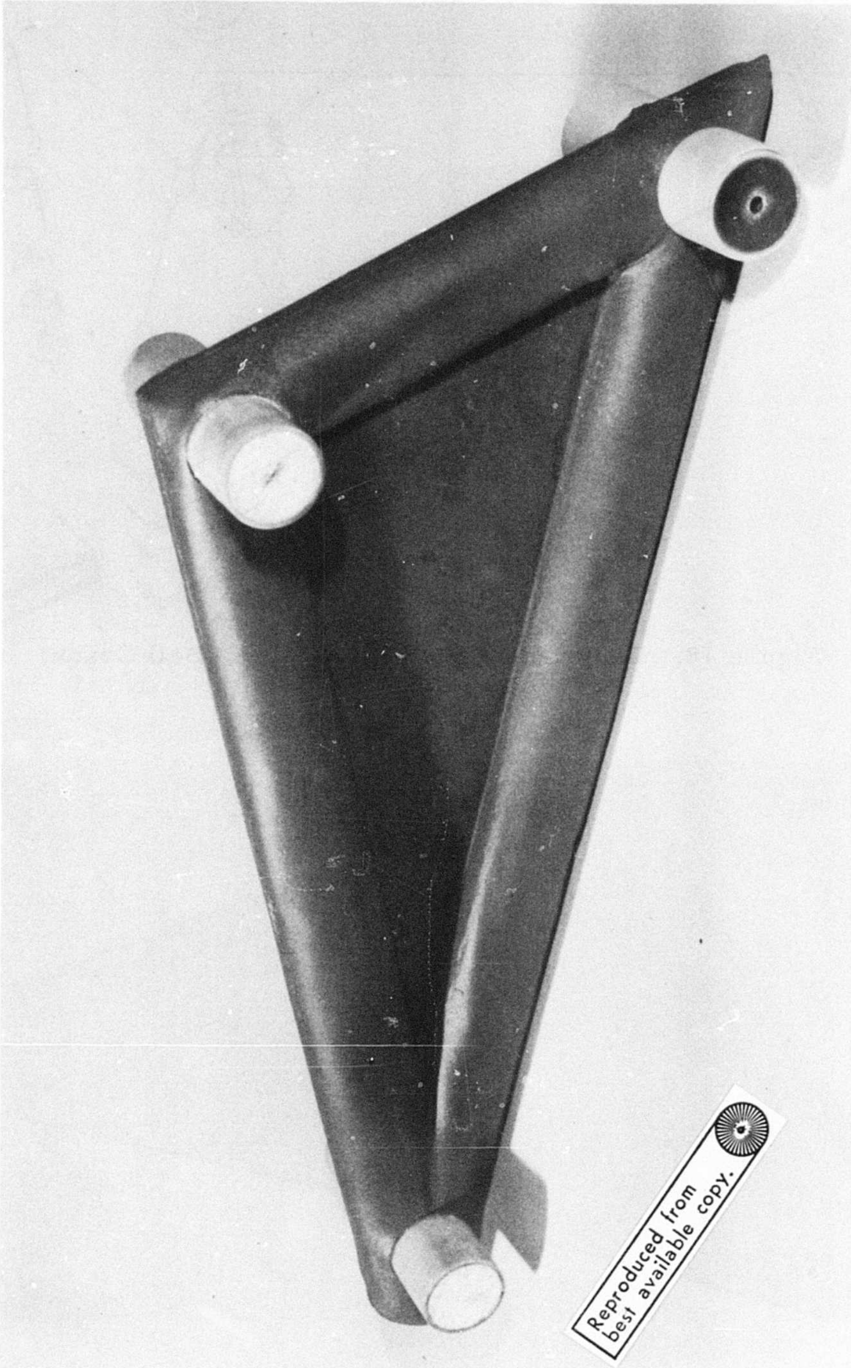

Figure 17. Tubular Bell Crank After Assembly.

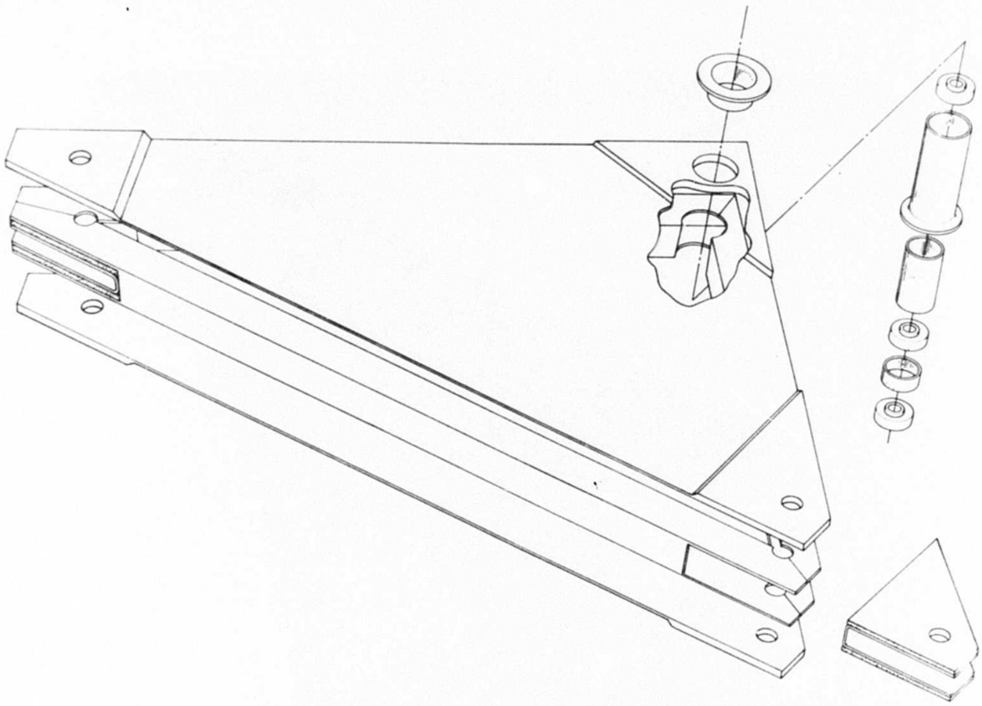

Figure 18. Exploded View of Square Tube Bell Crank.

Figure 19. Square Tube Bell Crank After Assembly.

TESTING OF BELL CRANK

Test Equipment

Static, dynamic, and ballistic tests were conducted on the components to evaluate their behavior. A 10,000-pound-capacity closed-loop hydraulic test machine was used to perform the static and fatigue tests. Loads were monitored with a Brush recorder, a recording oscilloscope, and an X-Y plotter. Cyclic frequency for all fatigue tests was 10 Hertz.

Static preloads for the ballistic tests were achieved with a simple screw jacking system. Loads for the ballistic tests were monitored with strain gages bonded to the input push rod and measured with a digital voltmeter. The bell cranks were impacted with .30-caliber armor-piercing ammunition at an approximate velocity of 1800 fps. Tumbling of the projectiles was achieved with a smooth bore rifle with the barrel end cut at an angle.

Projectile velocities were measured with electronic witness plates spaced 4 feet apart and a high-speed digital counter. Photographic records of each ballistic test were taken with a 35mm camera operating at 18,000 frames per second. A high-speed flash device triggered by the projectile passing through two charged pieces of aluminum foil separated by a thin tissue paper was used for 70mm stop-motion photography (see Figure 20).

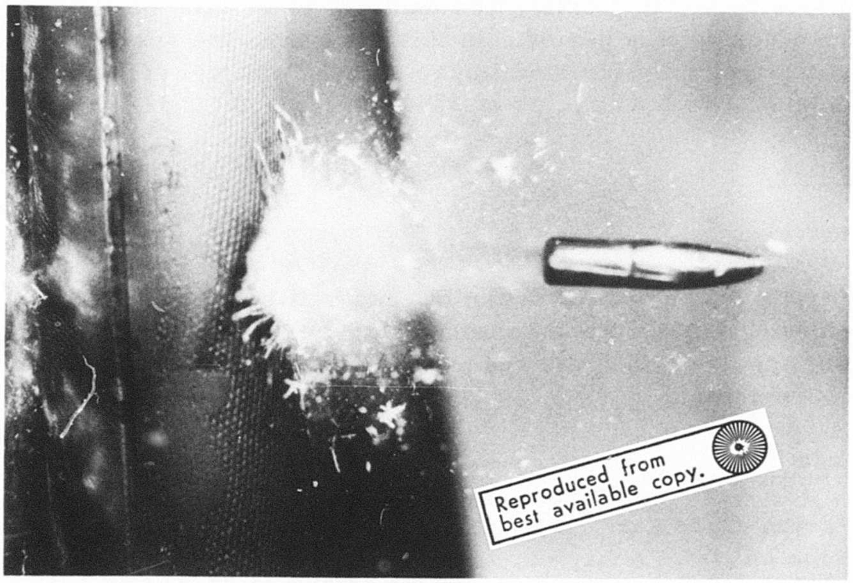

Figure 20. Impact Damage on Fiberglass Tubular Specimen; Flash Duration 0.5 Microsecond.

Flight Loads

The existing CH-47 forward bell crank is subjected to flight loads typically less than ±100 pounds. The highest measured values have not exceeded 135 pounds. Both pilots can exert a maximum load of 562 pounds on the component. The controlling factor, however, is the parked load condition when the hydraulic boost has bled down. Under the worst conditions, the component can be subjected to a compressive load of approximately 2000 pounds.[2]

In a current contractual research program conducted by Boeing-Vertol, the proof loads have been set at 1860 pounds for static compression and ±350 pounds for dynamic loading. The components studied in this program were designed for a proof load of ±4000 pounds at room temperature and ±350 pounds for dynamic loading. A proof load of 4000 pounds at room temperature was selected to assure a reasonable degree of confidence of withstanding the 2000-pound load at 180°F (operational requirement), since there is approximately a 40- to 50-percent reduction in strength at that temperature.

Under combat conditions, the probability of receiving more than two hits in a single area is small. After receiving damage, an arbitrary requirement of 30 minutes of flight time was considered sufficient (for this investigation) to get the damaged helicopter back to base or at least into safe territory. Typically, 100 load cycles at ±100 pounds might be experienced during this period. In this program, the specimens were subjected to eight fully tumbled impacts at the critical velocity and a minimum of 10,000 load cycles at ±350 pounds.

Test Results

General

The results of the static, dynamic, and ballistic tests are shown in the following table. All the components were not subjected to the full test spectrum in those cases where the design concept proved to be insufficient.

Ballistic Tests

The "Tetra-Core" and all the glass cloth components demonstrated desirable ballistic behavior, i.e., the damage was confined to the impact area, and spall was at a minimum (see Figure 20). However, an interesting phenomenon was observed during the tests. Consistently, the damage on the exit side of the sandwich-type components was

STATIC, DYNAMIC, AND BALLISTIC TEST RESULTS					
			Ballistic Data		
Type Test	Load (lb)	Cycles Applied, Frequency 10 Hz	Tumbled/Untumbled	Obliquity	Remarks
"Tetra-Core" Bell Crank					
Static	±400				
Fatigue	±350	100,000			
Static	-590				
Ballistic	+390		Tumbled	0 deg	
Fatigue	±350	10,000			
Ballistic	+390		Tumbled	0 deg	
Fatigue	±350	10,000			
Ballistic	+390		Tumbled	45 deg	
Ballistic	+390		Untumbled	0 deg	
Fatigue	±350	10,000			
Ballistic	+390		Tumbled	45 deg	
Ballistic	+390		Tumbled	45 deg	
Ballistic	+390		Tumbled	45 deg	Hit push rod fingers.
Ballistic	+390		Untumbled	45 deg	Impacted through input bearing and push rod fingers; complete freedom of movement ±22 deg after impact; only center push rod finger intact.
Fatigue	±350	10,000			
Fatigue	+700 -600	96			Failure of center push rod finger in tension (cyclic compressive loading of 0-600 lb maintained).
Static (New push rod fingers installed)	-3700				No failure.
Ballistic	+400		Tumbled	0 deg	Impacted through push rod fingers; one outside finger failed.
Static	+1500				Center finger failed; remaining finger operable at ±250 lb.
Clamshell Bell Crank (Fiberglass Tubular Bearings)					
Static	-3750				Complete failure; significant out-of-plane buckling began at 2000 lb.
Round Tube Bell Crank (Fiberglass Tubular Bearings)					
Static	+2750				No failure.
Static	-2425				Failed in tube joint at input bearing.

TABLE - Continued					
			Ballistic Data		
Type Test	Load (lb)	Cycles Applied, Frequency 10 Hz	Tumbled/Untumbled	Obliquity	Remarks
Square Tube Bell Crank (Fiberglass Tubular Bearings)					
Static (Bell Crank No. 1)	-2700				Bearing failure.
Static (Bell Crank No. 2)	-3350				Bearing failure at pivot point.
Static (Bell Crank No. 3, 12-Ply Doublers)	-4200				Tube failure (long member).
Nonoptimized Square Tube Bell Crank No. 1 (Existing CH-47 Bearings; Fit and Function) (6-Ply Tubes, 8-Ply Faces, 12-Ply Doublers, Wt=3.2 lb)					
Static	-5000				5/16 in. pivot pin failed.
Ballistic	+350		Tumbled	0 deg	
Ballistic	+350		Tumbled	0 deg	Partial delamination of exit face sheet.
Ballistic	+350		Tumbled	0 deg	
Ballistic	+350		Tumbled	0 deg	
Ballistic	+350		Tumbled	0 deg	
Ballistic	+350		Tumbled	0 deg	
Ballistic	+350		Tumbled	0 deg	
Ballistic	+350		Untumbled	0 deg	
Static	-1400				Partial failure of long tube.
Fatigue	±50	100			
Fatigue	±100	100			
Fatigue	±150	100			
Fatigue	±200	100			
Fatigue	±250	100			
Fatigue	±300	100			
Fatigue	±350	10,000			Maximum deflection within bell crank ± ≈ 1/4 in. Still operational at completion of test.
Optimized Square Tube Bell Crank (See Text)					
Static	-6100				Bell crank failure due to input pin failure; still operable at ±350 lb.
Ballistic (8 impacts)	+350		Tumbled	0 deg	Minimum damage.
Fatigue	±350	10,000			Still operable.

significantly greater than on the entrance side (see Figures 21 through 24).

It is believed that the damage was partially caused by a pneumatic-ram effect. A similar phenomenon has been observed in fuel tanks and is attributed to hydraulic ram. A separate research effort was conducted to determine if this pneumatic-ram effect could be eliminated. Four types of glass cloth sandwich construction were studied:

1. Foam-filled box

2. Closed box without foam

3. Open-ended box

4. Box with openings of various sizes on one side

Typical entrance damage for these configurations is shown in Figure 25. The damage on the entrance side is essentially the same for all four designs. In the foam-filled and the closed boxes, the damage on the exit side is quite severe, with considerable "petaling" (see Figure 26). On the open-ended box, the entrance and exit damage is essentially identical. For the box with various sized openings on one side, it was found that a vent as small as 1 inch square was sufficient to reduce the damage on the exit side to an acceptable level (see Figure 26).

Further studies using high-speed photography (18,000 frames per second) with a clear Plexiglas exit face sheet and also with photostress coating indicated that two phenomena were occurring. First, spall caused by the projectile impacting the entrance face sheet had higher initial velocities than the projectile and impacted the exit sheet before the projectile; second, a shock wave preceded the projectile. These phenomena produced observable damage on the exit face prior to the projectile impact. It is hypothesized that the combination of the spall and the shock wave preceding the projectile changed the surface energy of this exit face sheet and thus caused a detrimental change in its response when the projectile impacted. Apparently, venting reduces this effect.

In addition to these localized phenomena, in closed-cell sandwich construction the elastic response of the entrance face sheet caused by impact results in a drumming effect that tends to cause gross delamination in the bonds between the exit face sheet and the tubes. Venting also tends to reduce this effect.

The optimized square tube bell crank was designed without a foam core and such that it is naturally vented on the ends. A simple rubber flap bonded to the end attachment channel will be installed to keep dirt and moisture from accumulating in the interior of the bell crank. "Tetra-Core" without the balsa form is naturally vented.

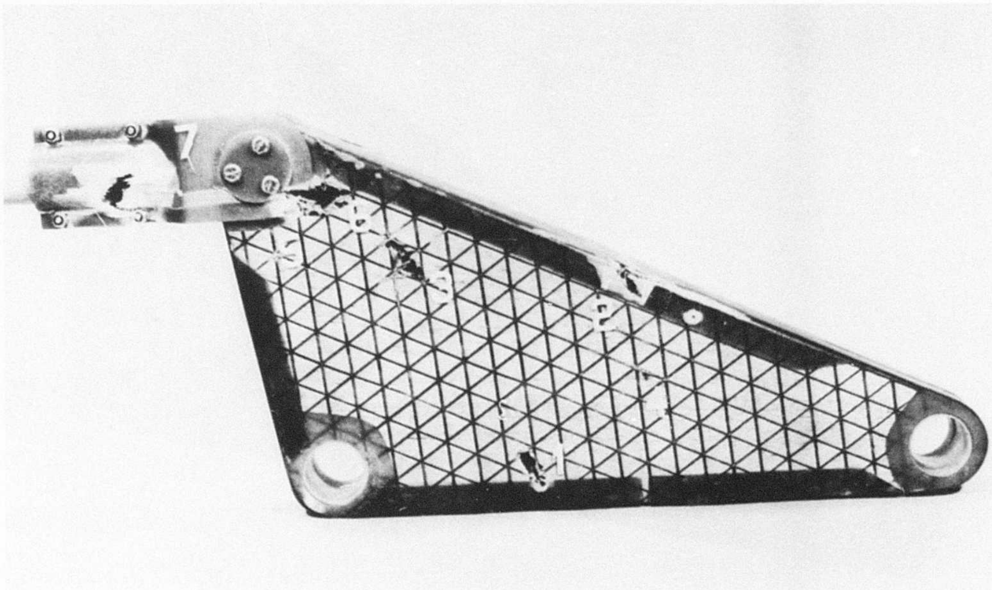

Figure 21. Ballistic Damage on "Tetra-Core" Bell Crank (Entrance Side).

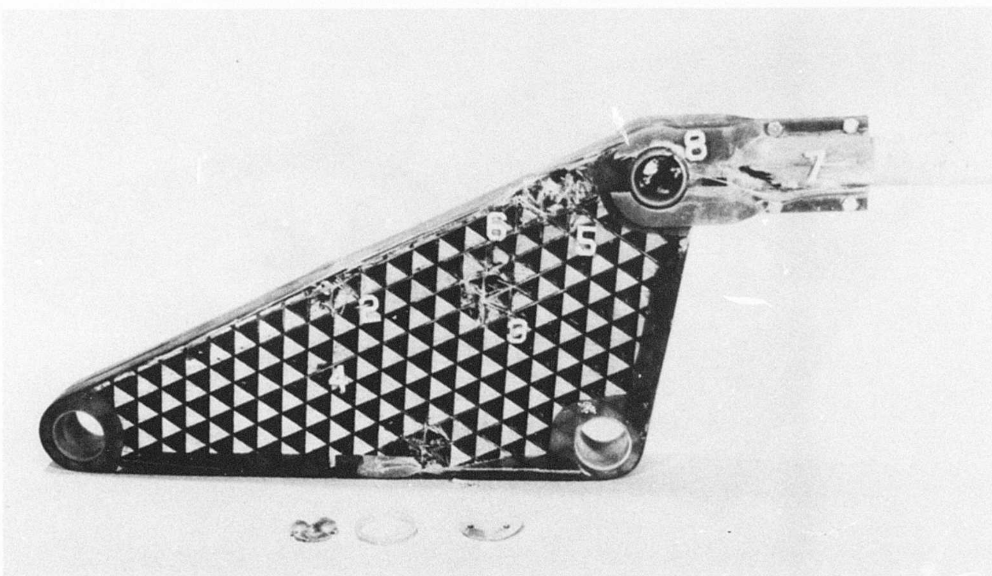

Figure 22. Ballistic Damage on "Tetra-Core" Bell Crank (Exit Side).

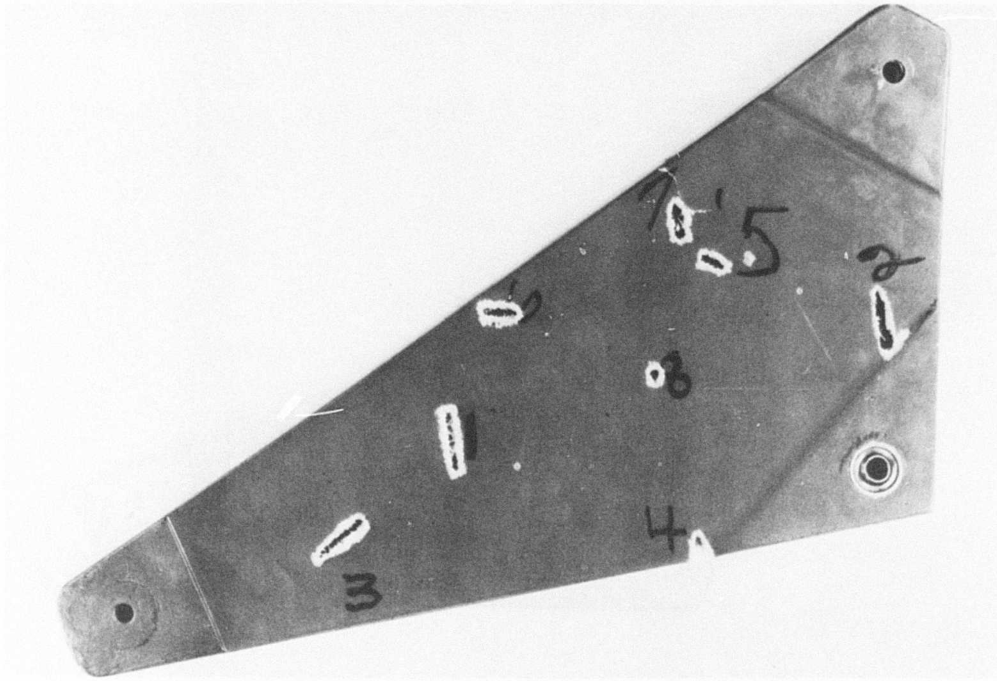

Figure 23. Ballistic Damage on Square Tube Bell Crank, Foam Core, Not Vented (Entrance Side).

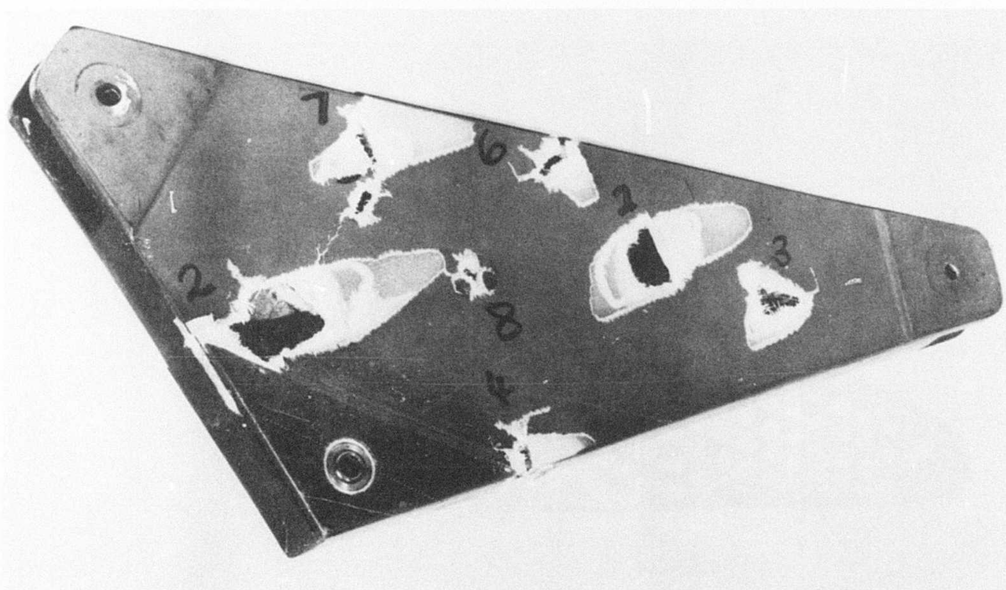

Figure 24. Ballistic Damage on Square Tube Bell Crank, Foam Core, Not Vented (Exit Side).

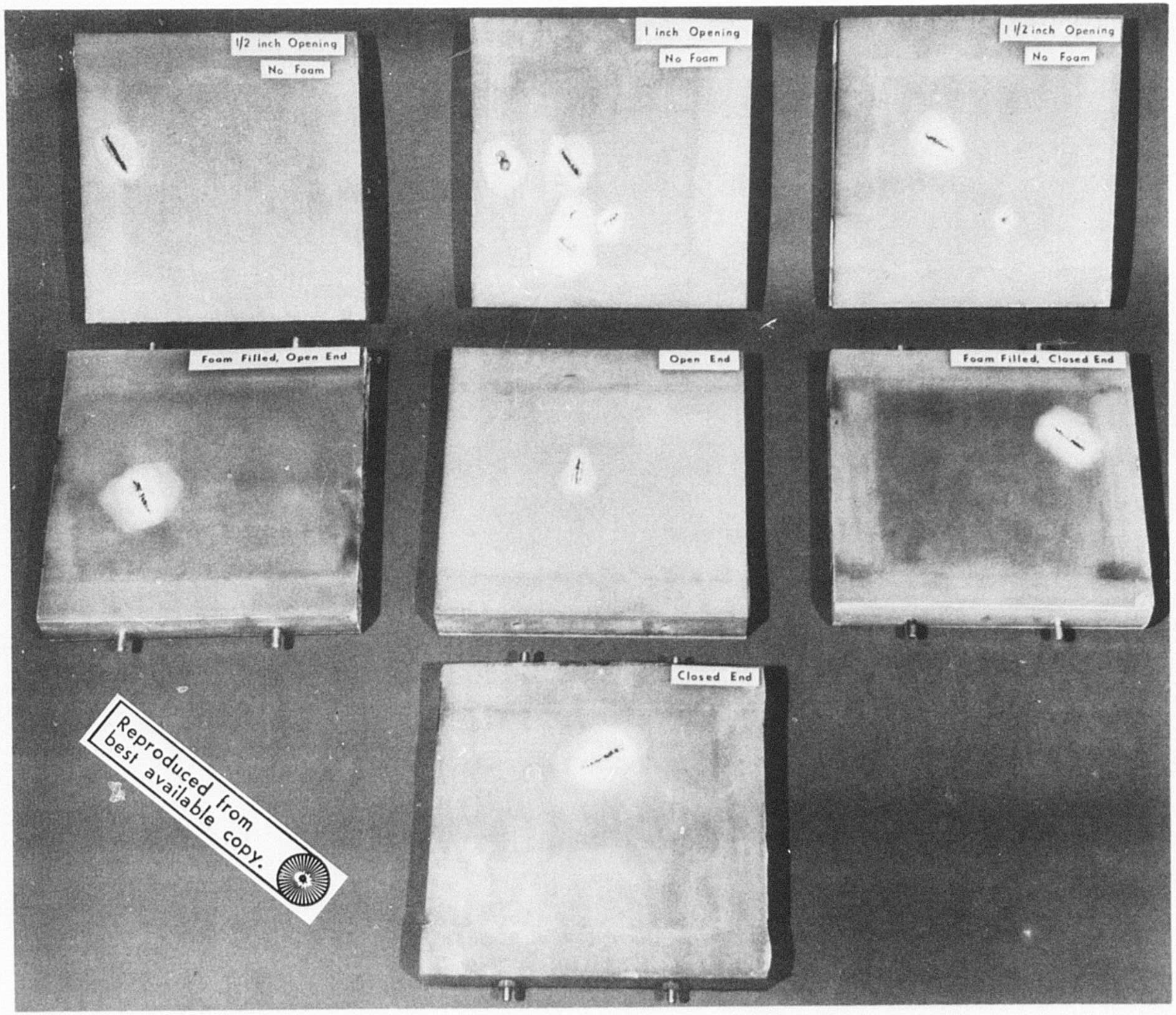

Figure 25. Typical Entrance Damage on Various Types of Sandwich Construction.

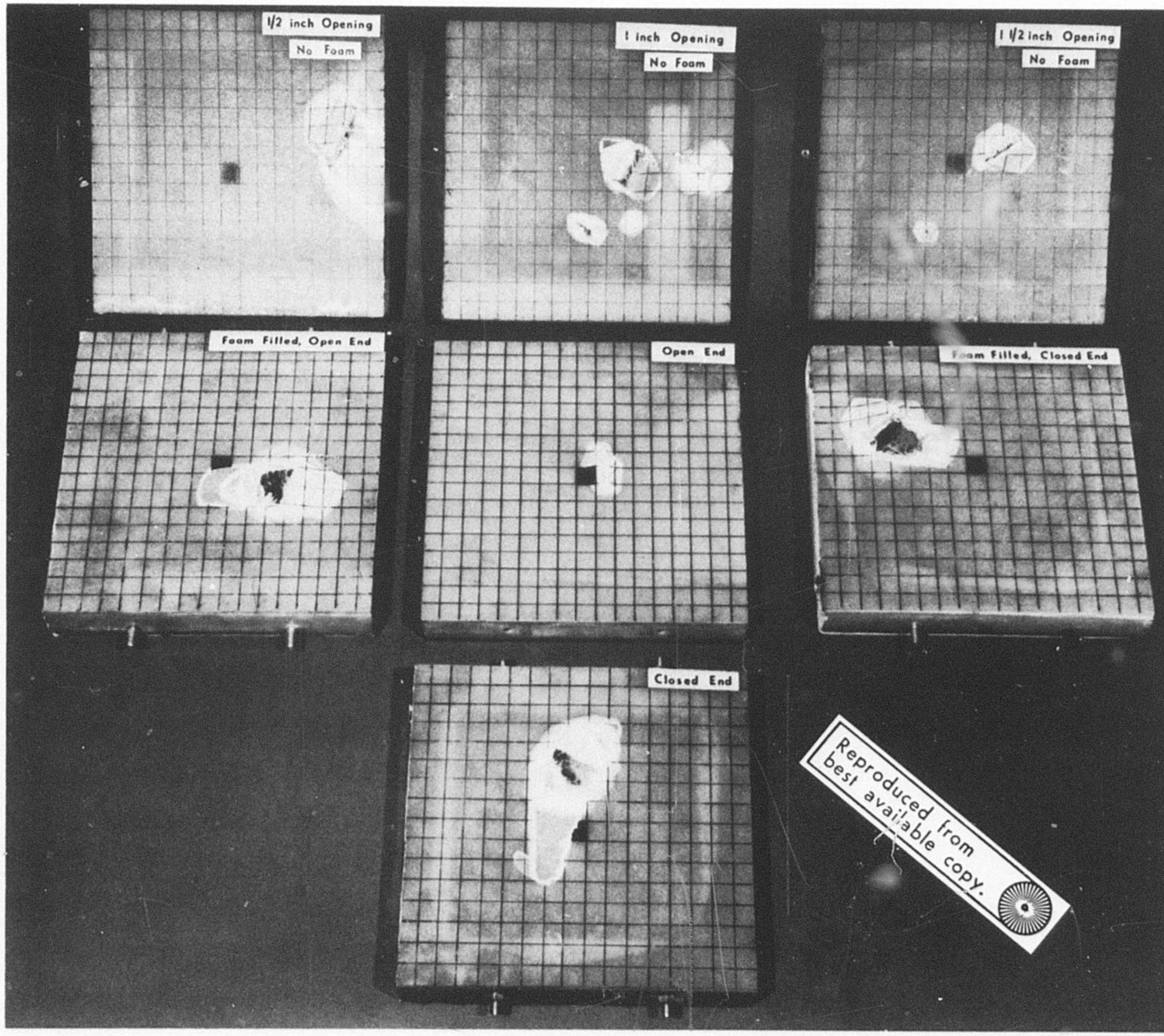

Figure 26. Typical Exit Damage on Various Types of Sandwich Construction.

BEARINGS AND PUSH RODS

DESIGN CONCEPT

In Reference 2, no attempt was made to achieve ballistic tolerance in the bearing and push rod attachment areas of the forward bell crank. Ballistic tolerance in these areas is considered to be significant, and therefore a limited effort was made to investigate ballistically tolerant bearings and attachments designed to take a fully tumbled .30-caliber projectile and still continue to function.

A ballistically tolerant bearing concept consisting of a large-diameter (nominally 1.45 inches), cylindrical fiberglass cloth bearing was developed that appears to offer the desired ballistic behavior. However, it should be noted that this design does not include a self-aligning feature.

FABRICATION

The glass cloth bearings were fabricated by wrapping six plies of 181 cloth/Epon 828 epoxy resin/DTA curing agent on a 1.30-inch-diameter rod and allowing it to cure, thus forming the inner sleeve. A single wrap of 0.003-inch-thick Mylar was then applied, followed by an additional six plies of cloth to form the outer sleeve. After curing, the Mylar was removed.

The push rod and bearing attachment was also designed to take a fully tumbled .30-caliber projectile and still continue to function. Again, the glass cloth approach was used as follows:

1. Eight-ply push rod was fabricated from 181 cloth/828 resin/DTA.

2. Twelve-ply center finger, 181 cloth/828 resin/DTA, was bonded to push rod, 828/DTA.

3. Eight-ply outer fingers, 181/828/DTA, were fabricated using matched molds and bolted to push rod.

4. Outer bearing sleeves were bonded in fingers, 828/DTA (Figure 27).

5. Bearing sleeves were cut to size (see finished bearing attachment, Figure 28).

TESTING

Test Procedure

The bearings were impacted with .30-caliber armor-piercing ammunition at an approximate velocity of 1800 fps. Tumbling was achieved with a smooth bore rifle with the barrel end cut at an angle. Projectile velocities were measured with electronic witness plates spaced 4 feet apart and a high-speed digital counter.

Test Results

Figure 29 shows the results of fully tumbled .30-caliber impacts of two of these bearings. Damage was localized and produced virtually no fraying at the edges of the damaged area, thereby allowing the bearing to function freely after impact.

Commercially available filament-wound bearings with Teflon coatings were also evaluated; however, due to the filament-winding technique, considerable fraying occurred that rendered the bearings inoperable after impact (see Figure 30). In production, a Teflon or sintered dry lubricant coating should be applied on the contact surfaces to improve wear and reduce friction.

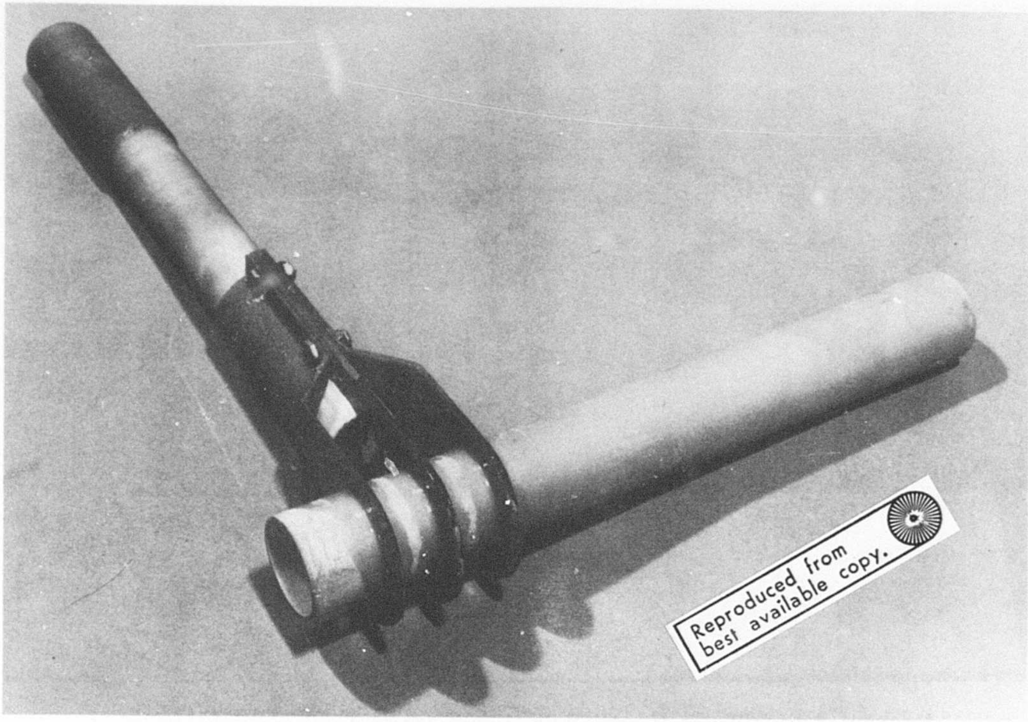

Figure 27. Alignment of Bearing Sleeves and Push Rod Fingers.

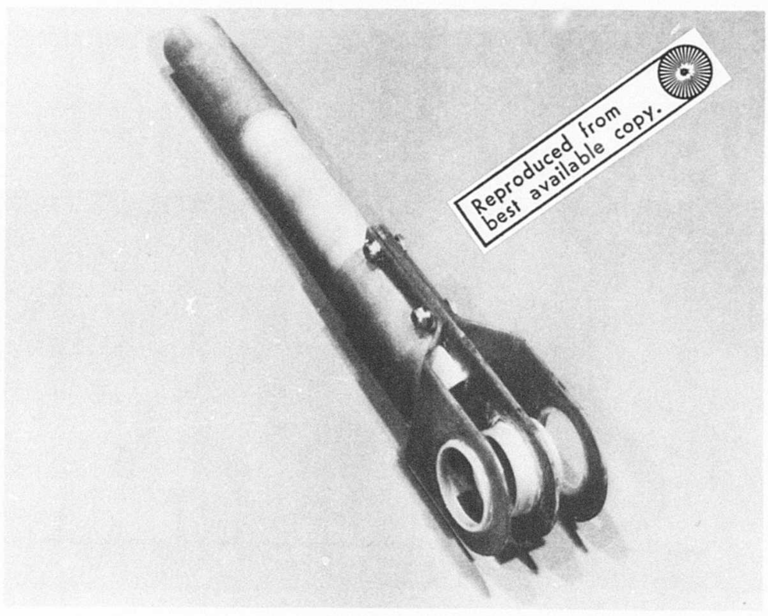

Figure 28. Completed Push Rod and Bearing Attachment.

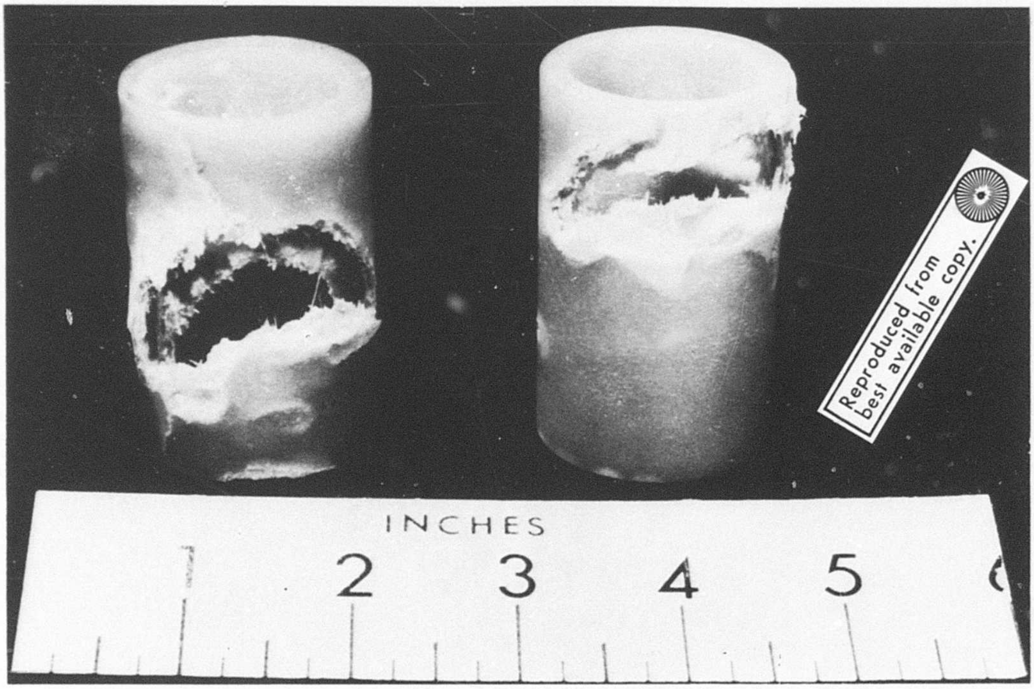

Figure 29. Glass Cloth Bearings After Ballistic Impact.

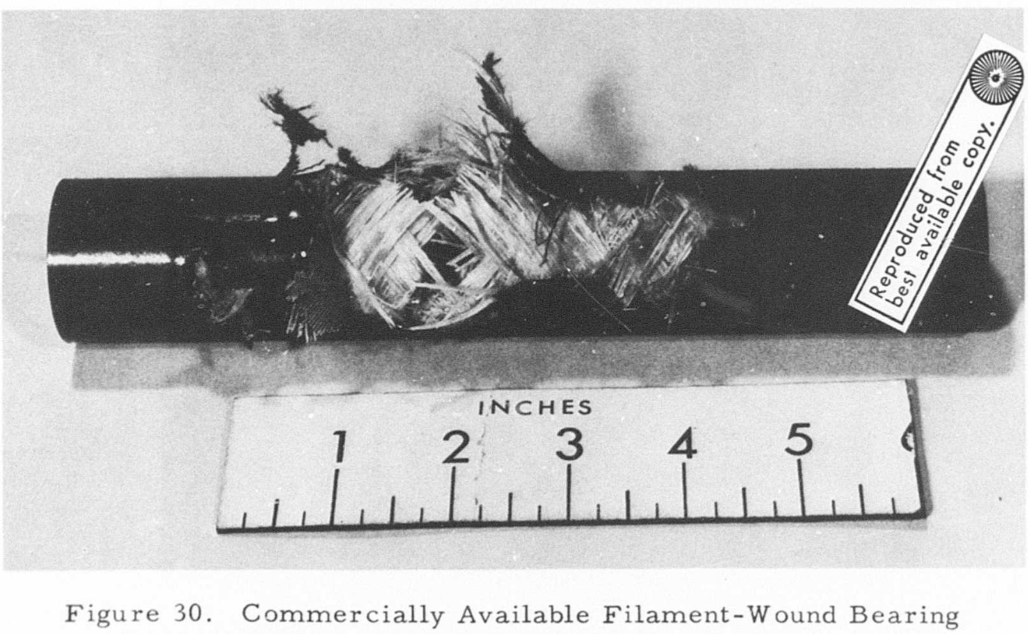

Figure 30. Commercially Available Filament-Wound Bearing After Impact.

EVALUATION OF CONCEPTS

The concepts investigated in this study result in significant improvements in weight and ballistic behavior over the existing CH-47 bell crank and significant improvements in producibility, weight, and cost effectiveness over the original composite bell crank developed in Reference 2. Weights of less than 2 pounds as compared to the weight of 3.4 pounds for the existing metallic bell crank can be readily achieved. Of the two basic concepts, "Tetra-Core" offers structural superiority, whereas the glass cloth offers ease of fabrication and cost effectiveness superior to the existing metallic components. It was found that venting reduced the damage on the exit side of the glass cloth specimens.

In addition to the significant improvements in bell crank performance, ballistically tolerant push rods and bearings were also developed. Limited research on the components indicates favorable tolerance to ballistic impact.

Research is continuing on these components. The technology developed thus far appears to be adaptable to other flight control components.

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13. ABSTRACT

The overall objective of this research program was to investigate a ballistically tolerant, lightweight, low-cost flight control system for the forward rotor control of the CH-47 helicopter. Both "Tetra-Core" (a three-dimensional, filament-wound space structure) and tubular fiberglass cloth concepts were evaluated. Weights of less than 2 pounds were achieved, as compared to 3.4 pounds for the existing metallic bell crank. Of the two basic concepts, "Tetra-Core" offers structural superiority, whereas the glass cloth offers ease of fabrication and cost effectiveness superior to the existing metallic components. It was found that venting reduced the damage on the exit side of the glass cloth specimens. In addition to the bell crank, ballistically tolerant push rods and bearings were investigated. Limited research on the components indicates favorable tolerance to ballistic impact, along with potential weight and cost savings.

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